

EDR 90258

Conceptual Design Study Of A Closed Brayton Cycle Turbogenerator For Space Power Thermal- To-Electric Conversion System

Final Report

Jeff L. Hansen
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1.0 Summary

A conceptual design study was completed for a 360kW Helium-Xenon closed Brayton cycle turbogenerator. The selected configuration is comprised of a single-shaft gas turbine engine coupled directly to a high-speed generator. The engine turbomachinery includes a 2.5:1 pressure ratio compression system with an inlet corrected flow of 0.44 Kg/sec. The single centrifugal stage impeller discharges into a scroll via a vaned diffuser. The scroll routes the air into the cold side sector of the recuperator. The hot gas exits a nuclear reactor radiator at 1300°K and enters the turbine via a single-vaned scroll. The hot gases are expanded through the turbine and then diffused before entering the hot side sector of the recuperator. The single shaft design is supported by air bearings. The high efficiency shaft mounted permanent magnet generator produces an output of 370 kW at a speed of 60,000 rpm. The total weight of the turbogenerator is estimated to be only 123 Kg (less than 5% of the total power plant) and has a volume of approximately 0.11 m³. This turbogenerator is a key element in achieving the 40 to 45% overall power plant thermal efficiency.

2.0 Introduction

Under Order No. H31376D to NASA MSFC, Allison Advanced Development Company (AADC) conducted a conceptual design study of a Helium-Xenon closed Brayton cycle turbogenerator for a nuclear thermal-to-electric power conversion system.

A commercial need for a space vehicle that serves as a satellite 'tug boat' has been identified. This vehicle would retrieve satellites in need of repair from high earth orbit to rendezvous with a shuttle in low earth orbit and ferry satellites from the shuttle to high orbits. This vehicle could also be used to reposition satellites to their proper or alternate positions. Additionally, numerous civilian space missions would be enhanced or enabled by electric propulsion system in the 50 to 4000 kWe range.

The requirement for the propulsion system of such a vehicle is to provide full power continuously for more than three years without refueling. A candidate electrical power source is a closed Brayton cycle nuclear thermal-to-electric conversion system. The main components of this system consist of a nuclear reactor, gas turbine engine, generator, recuperator and radiator. A schematic of this type of system is illustrated in Figure 1.

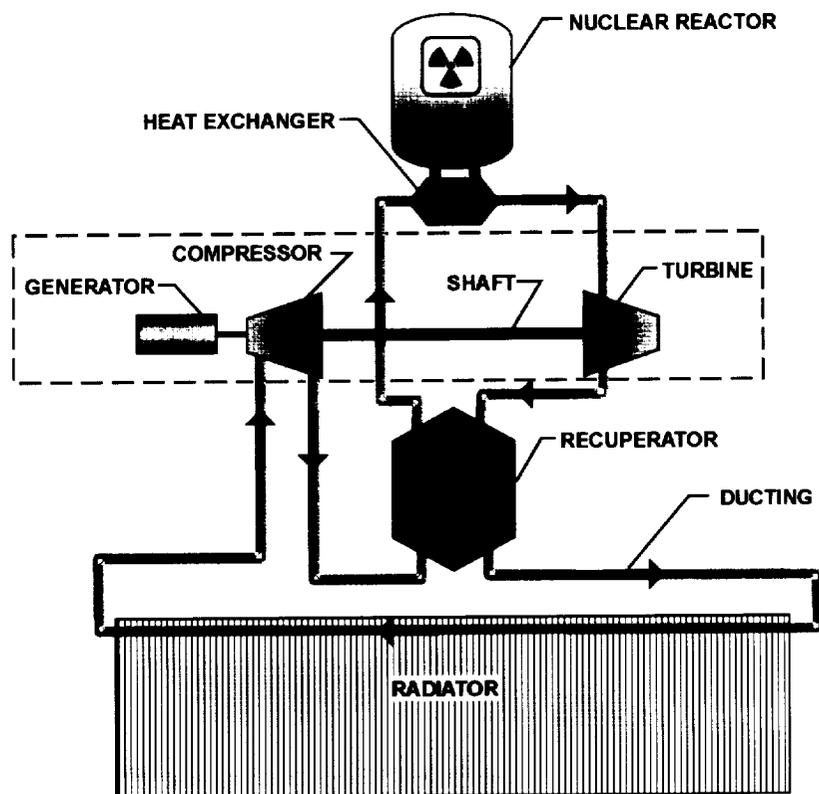


Figure 1. Schematic of a closed Brayton Cycle, thermal-to-electric power conversion system.

The focus of this study is the feasibility of turbogenerator portion of this power conversion system. The turbogenerator components are highlighted in Figure 1 and consist of a compressor, turbine, generator and power electronics.

The preliminary design of these components was based on existing, modified, and new turbogenerator components using results from previous research and development programs. The following studies were undertaken as part of this activity.

- Development of a preliminary configuration layout of the options which best satisfy the requirements based on trade-off studies,
- Definition of subsystems to be designed and/or procured,
- Identification of potential areas of risk,
- Define a development schedule including rough order of magnitude cost to demonstrate a turbogenerator system.

This report summarizes the results of the preliminary design activity.

3.0 Overview of Turbogenerator System Trade Study

AADC conducted a preliminary design trade study to determine the feasibility of a closed Brayton cycle turbogenerator for space power. The information resulting from this exercise provides an early indication of technical and program risks prior to committing to a detailed design and development program.

The study was initiated by identifying a baseline turbogenerator configuration, based primarily on Allison's TG1140A turbogenerator system. All aspects of the turbogenerator system were considered, with the following primary trades being discussed in more detail in subsequent sections of this report:

- He-Xe working fluid vs. air
- 1-shaft vs. 2-shaft turbine system
- compression ratio
- compressor configuration
- turbine inlet temperature
- gas bearings vs. oil bearings
- generator type
- regenerator vs. recuperator heat recovery system

The design state point conditions for a 360kW Brayton power system was provided by NASA MSFC. The cycle model was set up assuming a turbine inlet temperature of 1300°K and 2.0:1 cycle pressure ratio. Using this cycle data, baseline engine component sizes were estimated, from which a configuration layout drawing was generated. From this layout, preliminary weight and cost estimates were established. A preliminary generator specification was also created and provided to vendors to supply cost and performance information. Various alternatives to the baseline configuration were also considered. Decisions made when evaluating those options are discussed in the following paragraphs.

He-Xe working Fluid

The use of a working fluid other than air in a gas turbine engine is not standard practice at AADC and adds an element of risk to a development program. However, inert gases such as Helium have been used in closed systems and AADC has had some experience with preliminary designs of such systems. All of AADC's aerodynamic design and analysis tools have the capability of inputting any gas properties minimizing this risk. In addition, the mixture of 70% Helium and 30% Xenon has pertinent property values, such as density, similar to air.

Number of Engine Shafts and Mode of Operation

The selection of an engine configuration in terms of number of shafts and operating mode is almost entirely dictated by the intended application of the system. Since the operating power range of this application is expected to be near 100% output at all times, the best turbogenerator configuration is the single shaft, constant speed engine configuration. This configuration is commonly used in APU's, industrial and marine applications, and some turboprop aircraft applications. The simplicity of this configuration yields the lowest system part count and lowest system weight and cost. Two-shaft configurations cannot match the design point efficiency of the single shaft system because of added bearing and turbine transition duct losses. In addition, operation of a single shaft system in constant speed mode provides the best transient response to load demands of any turbine system.

Cycle Pressure Ratio

Unlike simple gas turbine cycles, where higher pressure ratio yields better fuel efficiency, optimum cycle pressure ratio for regenerative cycles is typically less than 3.5. The preliminary design study looked at compressor pressure ratios ranging from 1.9 to 3.0. The results of this study indicate that a pressure ratio of 2.5 is a good compromise between thermal efficiency and matching the turbomachinery with a direct drive high-speed generator.

Compressor Configuration

A preliminary design trade study was conducted on a matrix of design parameters consisting of pressure ratio, shaft speed, inlet pressure and entry type. This study was completed to explore the levels of compromise required between the compressor, turbine and generator. The matrix of compressor configurations examined is provided in Table 1 along with the estimated efficiency for each. The chosen configuration has a single entry and produces 2.5 pressure ratio at 60,000 rpm. This design also has the highest efficiency of those studied with a polytropic efficiency of 84.0%.

A dual entry configuration was considered because the specific speed is very high at 60,000 rpm and pressure ratio of only 2.0. The dual entry configuration lowers the specific speed and raises the efficiency significantly as shown in Table 1. A dual entry compressor also has a smaller diameter than single entry. However, the added complexity of the impeller and inlet system is a disadvantage and should be avoided if possible. A comparison of the dual entry configuration (2) and the single entry configuration (3) is shown in Figure 1.

Table 1. Compressor configuration trade study matrix.

CIP = 1.5 MPa					
Config.	Entry	Pr	rpm	Poly. Eff.	Dia. inches
1	Single	2.0	60,000	Base	8.5
2	Dual	2.0	60,000	+3.4%	8.0
3	Single	2.5	60,000	+4.5%	9.2
4	Single	2.0	50,000	+3.7%	9.7
CIP = 0.75 MPa					
5	Single	2.0	60,000	-2.5%	10.4
6	Dual	2.0	60,000	+2.8%	9.5
7	Single	3.0	60,000	+4.3%	10.9
8	Single	2.0	45,000	+3.3%	12.1

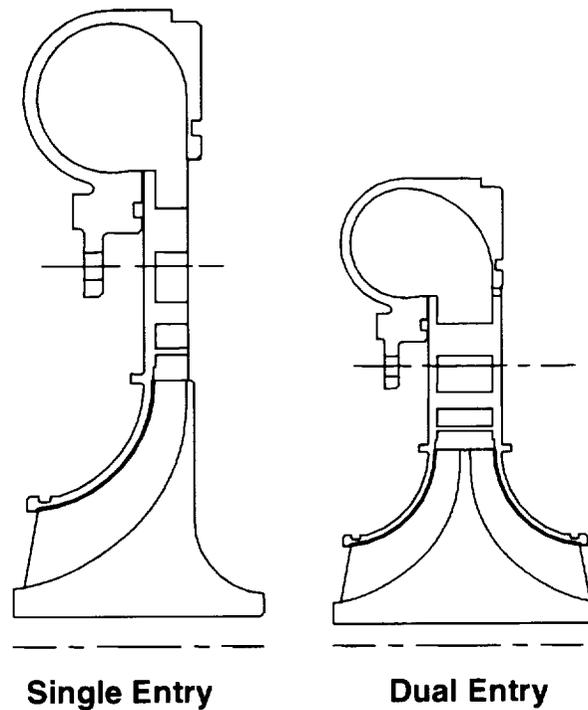


Figure 2. Comparison of a single and dual entry centrifugal compressor.

Turbine Inlet Temperature

It is realized that maximum thermal efficiency is obtained at higher turbine inlet temperatures. However, higher temperatures negatively impact turbine life. From AADC's experience, it is

known that an increase of 20°K can reduce turbine life by as much as 50%. Preliminary analysis indicates that the desired life of 30,000 hours is achievable at 1300°K with conventional turbine materials.

Oil Bearings

Oil bearings offer low risk in terms of bearing development as they are widely used in all current Allison production engines. However, the use of oil bearings requires additional hardware in the form of an oil pump, oil tank, fluid lines, and oil cooler. The cost and maintenance associated with these items is eliminated by using gas bearings. Additionally, the lubrication system requires maintenance that is not feasible in a space-deployed system. Consequently, oil bearings were not considered a viable option. The benefits and risks of gas bearings are further discussed in more detail in Section 3.4.

Generator Type

As discussed in Section 4.5, several high-speed generator design approaches were considered. At this time, a permanent magnet generator has been selected as the preferred generator type for this application. This selection is based on the recommendations of Ashman Technologies, a high-speed generator supplier. The permanent magnet generator is a compact design with efficiencies greater than 92% achievable.

Regenerator (Optional)

Regenerators offer similar performance advantages as fixed recuperators, but are substantially smaller and lighter, with initial costs estimated to be less than a comparable recuperator system. A feasibility study of the use of a regenerator in a space power system is not part of the work scope for this program. However, the benefits of a regenerator over a recuperator are potentially very high, but at a higher risk, and should be considered during a detailed design phase. A more detailed description of a regenerator system is contained in Section 4.8.

4.0 Description of Selected Turbogenerator Configuration

After evaluating the performance and costs of the baseline configurations and the alternative configurations, Allison selected a turbogenerator configuration that would provide the lowest risk to NASA. A conceptual layout of the selected turbogenerator system is shown in Figure 3. The turbogenerator is comprised of a single-shaft gas turbine engine coupled directly to a high-speed generator. The generator is mounted ahead of the power section inlet to minimize operating and soakback temperatures for improved efficiency and reliability. The generator employs a permanent magnet rotor with a high strength casing to allow continuous high-speed operation. The generator serves as a starter motor in addition to providing electrical power.

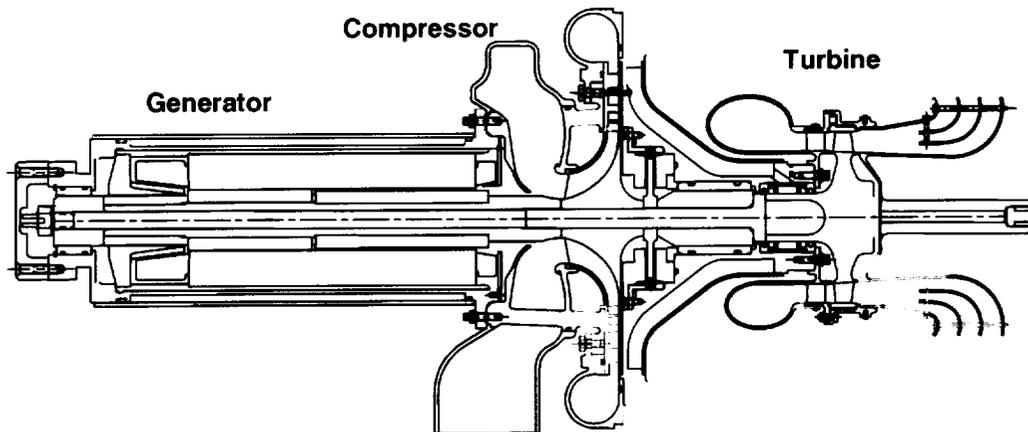


Figure 3. The conceptual layout of the selected configuration shows a simple and compact design based on previous Allison experience.

The engine turbomachinery includes a 2.5:1 pressure ratio compression system. The efficient single centrifugal stage impeller discharges into a scroll via a vaned diffuser. The scroll routes the air into the cold side sector of the recuperator.

The hot gas exits the nuclear reactor radiator and enters the turbine via a single-vaned scroll. The hot gases are expanded through the turbine and then diffused before entering the hot side sector of the recuperator.

The single shaft design is supported by air bearings, which eliminates standard lubrication system servicing and reduces system cost. Fixed geometry components are used for simplicity and any required engine cooling is provided internally using compressor discharge air.

4.1 Compression System

Preliminary sizing of the compressor section was performed based on the air flow and pressure ratio requirements of the engine as identified by the preliminary performance cycle

from NASA. Corrected airflow at the design condition is 0.44 Kg/sec at a pressure ratio of 2.5:1. Compressor polytropic efficiency is predicted to be 84%. AADC's compressor aerodynamic design and development experience coupled with the use of advanced fluid dynamic design tools, including 3-D, viscous codes, will facilitate the development effort, enabling these goals to be realized.

The preliminary design of the compressor section is based on a combination of Allison automotive and aircraft engine experience with designs of this general size. The compression system, shown in Figure 4, is comprised of a single-stage centrifugal impeller with a vaned diffuser and single exit scroll. The impeller design includes a combination of both full and partial blades for optimum aerodynamic performance. The modular scroll section collects and routes the compressor discharge air through a single exit to be ducted to the recuperator.

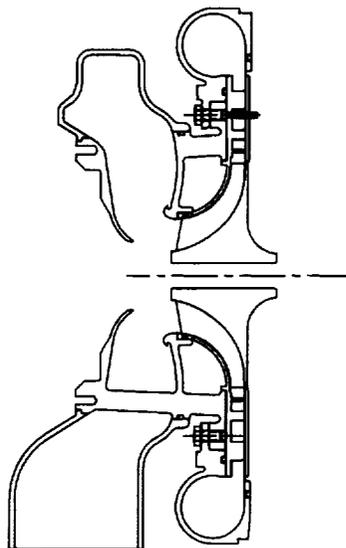


Figure 4. The compression system includes a single stage centrifugal impeller, vaned diffuser and single exit scroll.

The preliminary performance analysis predicts compressor flowpath temperatures suitable to allow the use of stainless steel in the impeller design. Impellers of this size are typically machined to achieve the thinner airfoils and smaller fillet radii necessary to obtain the aerodynamic performance goals. This is important since compressor efficiency has a significant impact on engine efficiency. Final material selection will be based on detailed stress analysis of each component with emphasis on system integrity.

The preliminary design of the compressor assembly is similar to that used in the Allison TG1140A. This configuration provides easy assembly and installation of compressor components for inexpensive manufacturing and assembly. Given the positive aspects of this configuration, Allison was unable to identify any additional improvements or design features

during the preliminary design phase.

4.2 Turbine System

The turbine system is comprised of an inlet volute and guide vanes, an integrally cast single stage turbine, and a turbine diffuser exhaust duct and is shown in Figure 5. The turbine design was a 110% scale from Allison's TG1140A Hybrid automotive turbogenerator. The turbine adiabatic efficiency is expected to be 81%. This low efficiency is attributed to the small size effects including large losses associated with blade tip clearances. The assumed tip clearance may be reduced significantly since operating transients are not an issue for this application. Since the turbogenerator operates at a constant speed and does not require a quick start-up, the running blade tip clearances can be reduced from typical gas turbine engine applications. An increase of 2 to 3% may be realized during the detailed design phase.

The axial turbine blisk is planned to be cast of MAR-M247 and inertia welded to a 410 SS shaft that ties the turbine, compressor, and bearing journal together. Air pulled from the compressor will cool the air bearings and the turbine. The amount of flow is controlled by either a single seal or flow restrictor.

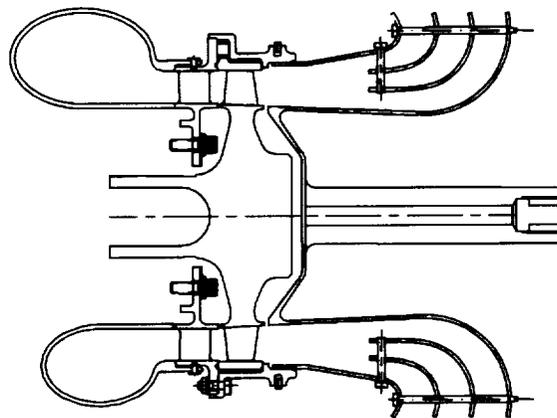


Figure 5. The turbine components are similar to the Allison TG1140A.

The axial inlet volute preliminary design was scaled from the Hybrid design that used a 3-D CFD (computational fluid dynamic) solution to set the guide vane span for 20 vanes. The predicted total pressure losses were 1.5% for the bend and volute and 5.3% for the vanes. Effort will be made during the detailed design phase to further reduce these losses. This may be possible since the Hybrid design was somewhat compromised by packaging constraints specific to that application. The volute may also be changed to gain fabrication advantages with relaxed space constraints. The axial inlet volute is supported to the bearing housing

(similar to the TG1140A) to reduce stress and allow for relative thermal expansion.

The preliminary diffuser was also scaled from the TG1140A design, but will likely be changed in the final design to better direct the flow through a single exit collector to duct the hot gas to the recuperator.

As ceramic technology is developed, a single axial ceramic turbine may be considered for future design improvements. Ceramic technology would provide significant increases to both power and thermal efficiency from the same package size without impacting turbine life.

4.3 Shaft Dynamics

The turbogenerator shaft design is based on that used in the Allison TG1140A engine, and incorporates improvements from experience with that engine to improve reliability and maintainability. The power core rotor consists of a radial compressor and an axial turbine cantilevered from a bearing module. The three components, including the bearing module, are bolted together with a central tie shaft. The turbine and generator rotor systems preliminary designs are shown in Figure 6. They are coupled together by a flexible coupling shaft that transfers torque but is soft laterally and decouples the two rotors dynamically.

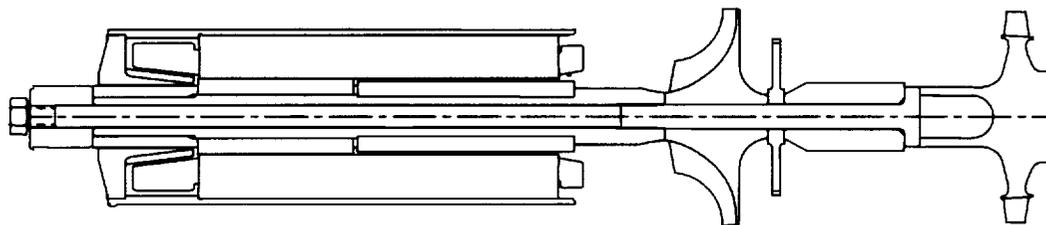


Figure 6. Bearings and Rotating Components

4.4 Bearings and Seals

For the unique space application of this turbogenerator, it is a requirement to eliminate all short-term (less than 30,000 hours) maintenance needs of typical gas turbine engines. For this reason, gas bearings were chosen over either rolling element or hydrodynamic oil journal bearings to eliminate the need for an oil lubrication system, oil dependent bearings and air/oil seals.

Hydrodynamic air bearings were selected over hydrostatic air bearings because they require

only the surrounding ambient air and not a high pressure air supply. Compliant foil gas bearings (CFB) were chosen because they proved robust in rotor shaft rig testing at Allison. The particular reversed multi-layered design made by R&D Dynamics was chosen for best rotor stability and damping because of higher hysteresis damping. Allison has worked with R&D Dynamics to develop a compliant foil bearing for turbine applications to be as successful as they have been for air cycle machines. In addition, on going gas bearing research at NASA GRC will be utilized during detailed design to achieve the most reliable and lowest risk configuration.

Gas bearing foils separate from the shaft due to self-generated pressures and become fully supported on a cushion of air at about 1500 rpm. The stiffness of the gas film cushion continues to increase with speed until the gas film is quite stiff at the highest speed. At this point, the bearing load capacity is typically 50 pounds per square inch of projected journal area. The dynamic stiffness and damping of the foil bearing is controlled by the corrugated foil in series with the stiffer gas film. Two adjacent smooth foils, wrapped in opposite directions, move relative to the corrugated foil producing additional coulomb damping for rotor stability.

Foil gas bearings offer the following advantages:

- Reliability is improved because there are fewer parts needed to support the rotating assembly and the foil touches the shaft only when the machine starts and stops.
- Operating efficiency is maintained at high and low temperatures where other bearings are no longer effective.
- Efficiency is improved with less parasitic losses at high speed.

The compressor and turbine are both overhung with two CFB journals between. A foil gas thrust bearing is nearest the compressor to control axial tip clearances. This same thrust bearing also supports the generator axial loads through the flexible shaft coupling. The journal air bearing, shown in Figure 7, is a unique, reversed multi-layered design that maximizes damping for a more stable rotor system. Bearings of this design are used in many air cycle machines for commercial aircraft, such as the 747, where mean times between failures of 100,000 hours have been demonstrated. The turbine rotor compliant foil bearing module is shown in Figure 8.

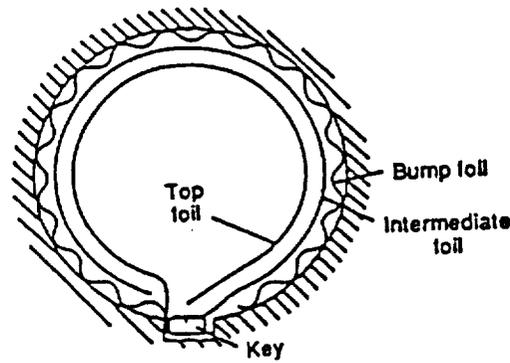


Figure 7. A schematic of a journal foil gas bearing.

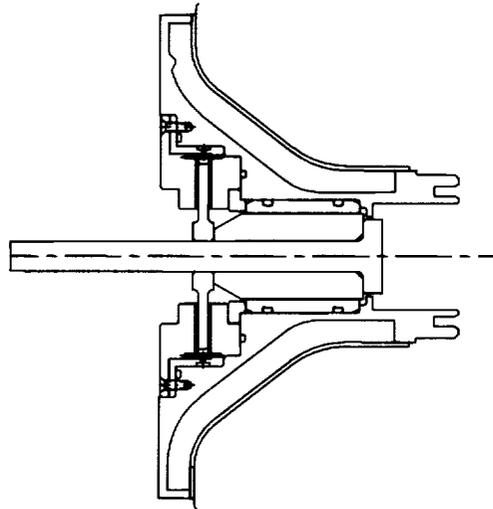


Figure 8. The gas turbine rotor compliant foil bearing module.

This design requires only one seal to restrict airflow between the compressor and turbine. This lab seal on the outside diameter of the thrust disk also provides some thrust balance to reduce bearing thrust loads. This seal is included in the bearing module and allows some cooling air down the shaft to cool the bearings and turbine rotor.

4.5 Generator and Power Control Electronics

The shaft-mounted generator system, which includes the starter/generator, control unit, and associated interconnecting cables and connectors, provides several functions. The starter/generator is capable of converting stored electrical energy into rotational mechanical

energy for purposes of starting the gas turbine engine. Once the engine is capable of producing net power, the electronic control switches the system into generate mode where rotational mechanical energy is converted into electrical power.

Through the efforts of previous programs, Allison has experience with various generator suppliers and types. All of these machines have favorable attributes and require further in-depth analysis before a final selection is made. Allison's previous experience with high-speed generators suggests that it might be advisable to have two generator suppliers during the development phase to minimize program risk. The generator options under consideration are discussed briefly in the following text:

Hybrid Homopolar

Allison currently has experience with this type of design on the TG1140A. The design combines a permanent magnet and homopolar design into one machine. The advantage of this design is that voltage can be varied at any speed by bucking or boosting the flux using the homopolar portion of the control. The primary disadvantage of this type of design is that the machine is larger than a pure permanent magnet machine and the air gaps are small in the homopolar flux return path. This machine would be considered to have moderate risk for high operating speeds. However, since the generator for space-power is essentially a constant speed generator, the advantage of this design is minimized.

Permanent Magnet (PM)

This design is significantly smaller than the Hybrid Homopolar and has been successfully used in several high-speed applications. The predicted efficiency for the machine and controller electronics is greater than 90%.

AC Induction Machine

This design is the largest of those evaluated. The efficiency is predicted to be comparable to the PM design. The AC induction machine will likely have the highest reliability and lowest production cost of those evaluated. Given the current state of development, Allison considers this design to have the lowest risk.

Axial Gap Permanent Magnet Machine

This design has been under development in England at the Imperial College for many years. The primary advantage of this design is that the magnet retention does not add to the air gap and stator iron losses are reduced. High-speed prototypes have been built and operated with one or two axial components. More axial components can be added for additional power. Allison considers the risk of this machine low, but requires more knowledge concerning development costs.

A permanent magnet generator was selected for the baseline configuration since Allison has experience with the PM design. In addition, a PM supplier, Ashman Technologies, was recommended by NASA. In start mode, the power control electronics converts DC power from the battery pack to current regulated, variable frequency, phased AC power to the PM motor which in turn generates torque on the engine shaft. In power generation mode, three-phase, variable voltage, variable frequency power from the generator is converted to DC power. The basic requirements of the generator and power conditioning unit supplied to Ashman Technologies for preliminary sizing is listed below.

- Generator output: 370 kW
- Speed: 60,000 rpm
- Power electronics output: 360 kW
- Power and DC bus Voltages: 1-3% 28 VDC (space bus power)
2-4% 130 VDC (avionics grade)
90-95% 1300 VDC (non-avionics grade)
- Overall efficiency: 92% minimum at 360 kW
- Operational Life: 3-5 years continuous

4.6 System Physical Characteristics

Preliminary analysis indicates that the 360 kW turbogenerator system weighs approximately 135 Kg. This estimate includes the components shown in Figure 3 plus associated power control electronics. A breakdown of weights by component is shown in Table 2. This table also shows the estimated weight and volume for a turbogenerator scaled to 100 kW and 1000 kW. During the detailed design, AADC will attempt to reduce system weight whenever possible without compromising system performance, or reliability. Thus, actual weight may be greater than or less than this estimate as design choices are made in the detailed design phase.

Table 2. Estimated component weights for three power levels.

Power Output Module	100 kW		360 kW		1000 kW	
	Wt. (Kg)	Vol. (m ³)	Wt. (Kg)	Vol. (m ³)	Wt. (Kg)	Vol. (m ³)
Turbomachinery	12	0.013	25	0.037	80	0.165
Generator	15	0.009	47	0.016	70	0.024
Power Electronics	18	0.017	62	0.054	87	0.076
Total	45	0.039	123	0.107	237	0.265

4.7 System Life

The preliminary assessment of the turbogenerator indicates the required life of greater than 30,000 hours with no maintenance is achievable. The primary features that contribute to the system long life compared to conventional land based turbogenerators include:

- The replacement of oil bearings and lube system with gas bearings
- Particle free working fluid prevents erosion of compressor and turbine airfoils
- Moderate turbine inlet temperature allows use of production high temperature super alloys

4.8 Regenerator System (Optional)

Regenerators are rotating heat recovery devices which transfer the energy from hot turbine exhaust gas (which would otherwise be wasted) to heat the air which enters the reactor heat exchanger. Hence, less fuel is required to achieve a given turbine inlet temperature, making the regenerative engine more fuel efficient than a non-regenerative engine. Regenerator ceramic technology provides heat exchangers that are compact, relatively lightweight, and possessive of excellent thermal fatigue characteristics.

The regenerator system consists of two regenerator modules, one bolted to each side of the engine housing. Each regenerator module consists of: a regenerator disk, cover, electric drive motor, ring gear and pinion mesh, associated seals, and base piece. The components are sandwiched between the cover and base piece as illustrated in Figure 9.

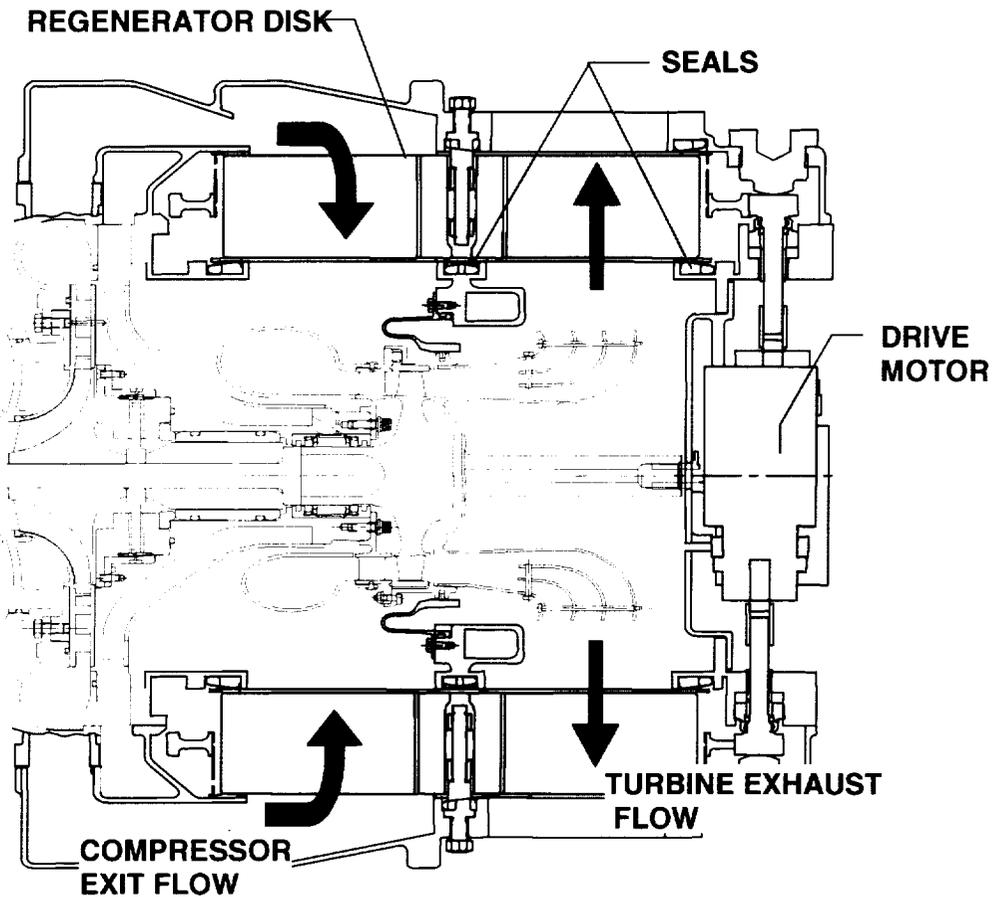


Figure 9. Diagram of the regenerator system preliminary design.

Each regenerator module utilizes a ceramic disk that is 25 to 30 cm in diameter and 5 to 8 cm thick. The disks for other Allison regenerators are produced by Corning, who is also the principal supplier of extruded ceramic catalyst bodies and diesel particulate traps to the automotive industry. The materials used for the regenerator disks in the turbogenerator are common with their automotive products. If the size of the disk for this application is larger than Corning's existing extrusion technology, it may be necessary to fabricate each disk by cementing smaller extruded segments together to form a complete disk.

The disks are supported at the hub by graphite bearings and ring gears are attached to the outer diameter of the disk and cured in place by silicon rubber. An externally mounted electric motor will drive a pinion meshed with the ring gear to turn the disk.

Compressor discharge air is directed through one sector of the disk, and turbine exhaust gas flows through the other sector as shown in Figure 9. The flows are kept separate by seals running against the disk faces. As the disk rotates through the turbine exhaust gas, it absorbs heat that is transferred by convection to the compressor discharge air.

The seals cover both the periphery and diametral disk faces with a "D" shape on both hot and cold sides of the disks. The seal systems are designed to provide low leakage and minimal wear. Leakage rates achieved on the regenerative Allison IGT 404 engine are typically below 4%. Seal technology being further developed under other Allison programs will be incorporated to ensure the best technology in terms of cost, performance, and reliability.

Regenerators vs. Recuperators

Regenerators offer several advantages over recuperators. The regenerator systems provide high thermal effectiveness at very low volume compared to recuperator type systems. A regenerator system can be made smaller and lighter than fixed recuperators can because the hot and cold fluid passages are in reality the same passages, rotated through the opposing-flow fluid streams. This counterflow of inlet air and exhaust gas is theoretically the most efficient heat exchanger arrangement (theoretically a long enough counterflow exchanger can achieve cold fluid outlet temperatures equal to hot fluid inlet temperature or 100% efficiency). Because recuperators must have alternately stacked hot and cold fluid passages, they normally are arranged in crossflow patterns to facilitate inlet and outlet manifolding. This crossflow arrangement reduces efficiency which, combined with the manifolds, increases recuperator size required to achieve efficiencies comparable to regenerators.

As part of a preliminary design effort for another program, a preliminary recuperator system was sized using an internally developed recuperator design system. The resultant configuration, which yields the same performance capabilities as the selected regenerator system, consists of two modules. Each module measures approximately 31 cm high x 64 cm wide x 31 cm long (minus ducting) weighing approximately 212 Kg. The weight of the recuperator system alone nearly doubles the weight of the entire turbogenerator system with regenerators.

Allison has over 22 years experience with regenerative gas turbine engine programs employing ceramic rotating disk regenerators. These programs include the AGT-5, AGT-6, CATE, AGT 100, Hybrid, M1 Abrams ASEP APU and ATTAP/HVTE TS. Regenerator development is actively supported by both engine and regenerator rig testing from the M1 APU program and HVTE-TS.

The Allison 404 engine, which powers Patriot missile systems, uses rotating regenerators. During development, these regenerators accumulated over 261,000 hours of testing. These regenerators are currently installed in fielded Patriot missile systems and have accumulated thousands of hours of operation, many under very adverse conditions (i.e., Desert Storm). These regenerators have performed very successfully.

A major disadvantage to regenerators is the life of the disks and seals. Currently, ceramic disks need replaced after 15,000 hours of operation and the seals after only 5,000 hours. To make regenerators practical for space applications these maintenance issues must be

addressed.

The life of the seals may greatly be increased if the efficiency loss is acceptable as the seals wear. A cycle study needs to be conducted to determine how much seal leakage loss can be tolerated before the performance advantage is lost. The seal life may be solved if a lower efficient but lighter regenerator system still has a better specific power than a recuperated system.

5.0 Program Risks

As with any new product development, a certain amount of risk is involved in providing a product within the development cost and schedule targets. Furthermore, a certain amount of risk must be taken in applying new technologies in a product design to meet unique requirements. AADC intends to minimize the development risk by applying similar designs and/or techniques implemented in existing products or programs. However, a certain amount of risk will still exist as a result of the implementation of the following developing technologies:

(1) Gas Bearings

Though gas bearings have successfully demonstrated over 100,000 hours of operation in air cycle machines, Allison's experience has been limited to shaft rig testing. One of AADC's development challenges will be to transfer this gas bearing technology to an engine environment. In addition, the gas bearings may not be adequate to support the high side loads produced by the generator. An alternative is magnetic bearings which AADC has experience with in an Air Force program. If it is determined that magnetic bearings are required, additional development risk, cost, and time will be incurred.

(2) Turbine Efficiency

The primary concern lies in the controlling of the turbine tip clearances to less than 0.010 inch. If the clearance cannot be maintained this tight, a loss in turbine efficiency will result, thereby negatively impacting thermal efficiency.

(3) High Speed Generator

Allison's experience with high-speed generators suggests that a new generator design could pose a risk item. Though it is unlikely one exists, AADC will search for an existing generator that meets the initial demonstration requirements. In any case, funding two generator suppliers during design and development is a recommended option to mitigate any risk.

(4) He-Xe Working fluid

Although considered a low risk item, AADC does not have significant experience with the use of non-air working fluid and how it influences turbomachinery and gas bearing performance.

(5) Regenerator Disks and Seals

Though theoretically attainable, the ability of ceramic regenerator disks to perform satisfactorily through 30000 hours of operation has not yet been demonstrated. The risk involves loss of thermal efficiency or early removal from service should this level of integrity not be achieved.

Current regenerator seal technology provides seals with an expected life of only 2500 hours. Though Allison is currently developing this technology in other programs, increasing the seal life to 5000 hours in the immediate future will be a significant challenge.

6.0 Development Schedule and Cost

A schedule for the development of near term demonstration of a closed Brayton cycle turbogenerator is shown in Figures 10 and 11. This schedule is based on the low risk findings of this study and past experience with the design, fabrication and test of similar systems. The development program is divided into two separate modules, the turbomachinery and the generator and power electronics. The development of the turbomachinery will be completed by AADC and its schedule is shown in Figure 10. The program schedule for the generator and power electronics is provided in Figure 11 and was provided by Ashman Technologies.

These schedules show that the turbogenerator will be available to NASA MSFC for demonstrator testing in 41 months after start of the program.

Included in these schedules are three options that address alternate configurations and a lower cost generator development approach.

Option 1: Regenerator Study

Study the practicality of a regenerator for a space power application. Primary focus is on cycle study trade-offs and disk and seal life extensions.

Option 2: Reduced Generator Development Effort

This option is a lower cost generator development program with fewer configuration studies and less analysis. This option significantly adds risk to the program and is not recommended based on Allison's previous experience with the development of high speed generators.

Option 3: Magnetic Bearings

This option is a risk reduction program for the gas bearings. AADC's experience with the high side loads produced by the generator is that the gas bearing may not be able to support this load. An oil-less alternative is magnetic bearings which AADC has experience with from an Air Force program to implement them in an advanced military gas turbine engine. This option would include a magnetic bearing rig test in AADC's facilities.

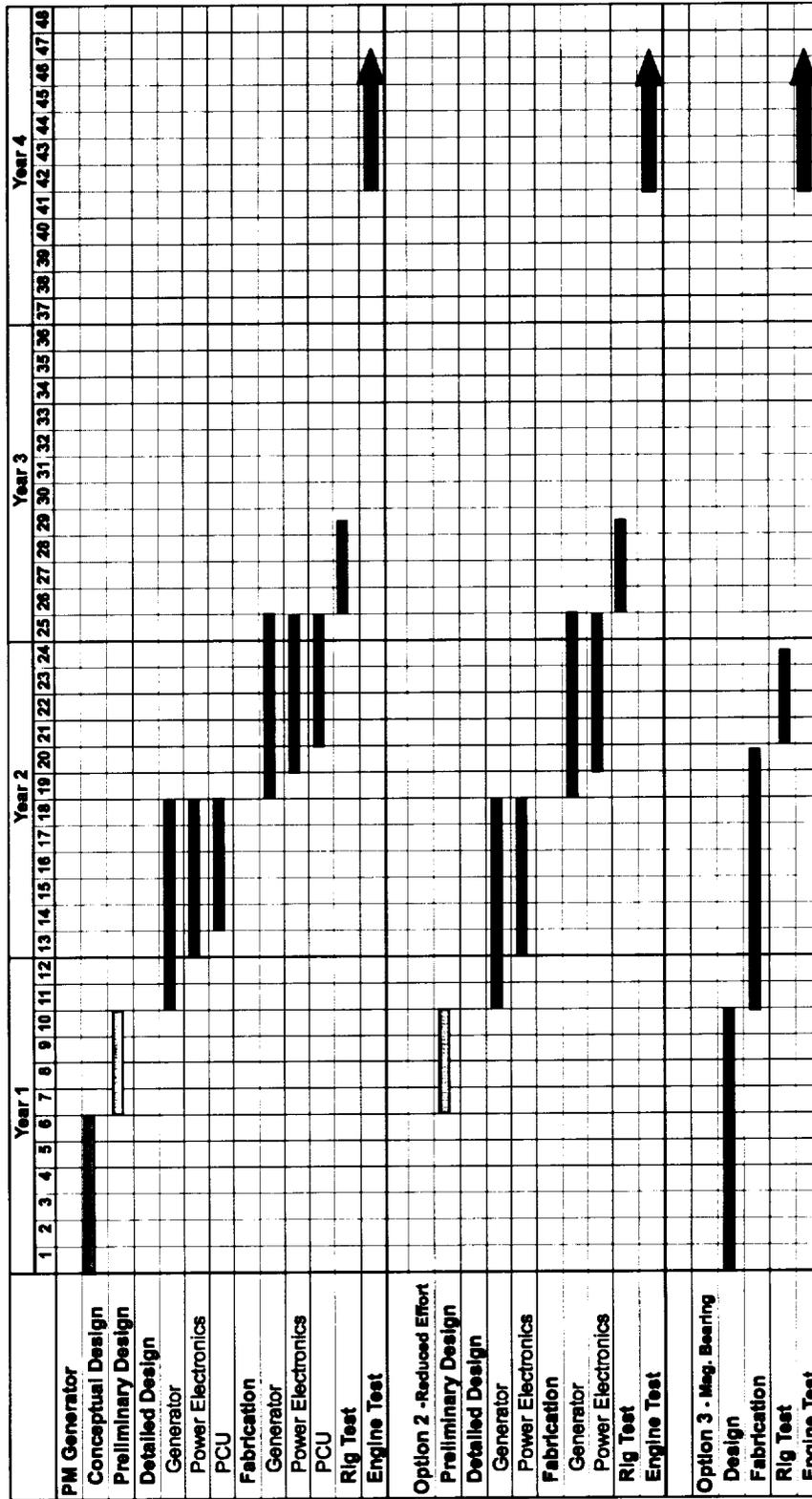


Figure 11. Permanent magnet generator and power electronics development schedule.

The total estimated cost to complete the baseline development program is \$3.5 million. This includes the design, analysis, fabrication, appropriate rig tests and support of the full system test at NASA's facilities. A breakdown of the total cost by task along with the estimated cost of the options is provided in Table 3.

Table 3. Estimated demonstrator development cost by task and options.

Component	Duration (Months)	Est. Cost (Thousands of \$)
Turbomachinery		
Design	31	2,410
Fabrication and Assembly	17	785
Test Support	5	307
Generator & PCU		
Base Effort	29	4,000
Base Program Total	46	7,502
Options		
(1) Regenerator Study	15	150
(2) Reduced Effort Generator	23	1,500
(3) Magnetic Bearings	24	1,000

7.0 Conclusion

The preliminary design effort performed by AADC has identified the most promising turbogenerator configuration to meet the goals of the thermal-to-electric conversion system for space power. The development schedule and cost of a demonstration engine including appropriate rig tests was provided. Areas of risk associated with this program were also identified.

This configuration will serve as the basis of the detailed design. In the detailed design phase, additional engineering design and analysis will be performed to maximize system thermal efficiency, minimize risk, and achieve the reliability. The detailed design of the selected configuration will benefit from Allison's extensive experience in small, regenerative engine design and development. This experience is derived from prior automotive efforts, such as the AGT-100, AGT-5, AGT--6, and TG1140A as well as the industrial IGT-404 which provides power for the Patriot Missile System and the TS1230A, an under-armor auxiliary power unit designed for the M-1 Abrams Tank System Enhancement Program.



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